Klamath River Reservoir Sediment Erosion and Trapping Model

An Excel spread sheet computer model was developed to help analyze the timing and intensity of suspended sediment concentrations in the Klamath River downstream of Iron Gate Dam as part of the analysis of potential impact following the removal of four dams on the Klamath River in southern Oregon and northern California. The elements of the model and methodology are discussed below.

Objectives

The model was created to provide a means of quickly analyzing effects from and comparing various approaches to lowering reservoir elevations and removing dams. This spreadsheet analysis provides a conceptual level understanding of effects of lowering the reservoirs on water quality downstream of Iron Gate Dam. The model considers the effects of trapping sediment coming in from upstream and re-eroding sediment in both Copco 1 and Iron Gate reservoirs. The model allows variation in start time, maximum reservoir lowering rate, outlet capacity, water year flows, river channel width and variation in settling parameters. The model uses Klamath River flow recorded at Iron Gate Dam from 1962 to 2006 as the basis for analyzing erosion of fine sediment.

Assumptions

The following assumptions were made in the analysis.

- Time increment for the simulation is one day (24 hours). Flow values used were for average daily flows rather than instantaneous values.
- The analysis does not include effects of surface erosion outside of the river channels or from river channel widening in successive high flow events.
- All the sediment eroded from J. C. Boyle resettles in Copco 1. All J. C. Boyle sediment smaller than .125 mm was added to Copco 1 eroded volume. J. C. Boyle has multiple outlets, none of them equipped with controls for flow regulation. Proposed methods of removing J. C. Boyle dam are discussed in the FERC report. For this analysis it was assumed that J. C. Boyle dam removal would occur before or at the start of lowering Iron Gate and Copco 1 reservoirs. Because of the relatively larger size of sediment particles, all sediment from J. C. Boyle was assumed to settle in Copco 1 reservoir.
- The width of the eroded section was discussed in the *Klamath River Dam and Sediment Investigation* report by Gathard Engineering Consulting conducted for the California State Coastal Conservancy filed with FERC in November, 2006. The predam river channel minimum width was assumed to be 200 feet wide. Additional erosion width included erosion of banks at a 10 to 1 slope from the bottom of the channel. The width of the equivalent rectangular section eroded for Iron Gate and

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Copco 1 was 266 and 265 feet respectively. The depth of the eroded section was based on elevation difference between predam and post dam bathymetry.

- Average grain size of the eroded material was based on borings completed in 2006. For both Iron Gate and Copco 1 reservoirs, approximately 78% of the material eroded was silt or smaller.
- Flow from tributaries was not included for this level of analysis. Mainstem flow was assumed to be the primary means of erosion, settling, re-erosion, and reservoir water surface elevation control for TSS considerations.
- Sediment erodes from the predam river channel and immediate overbanks only. Erosion from surfaces outside the river channel was not included in this analysis. Erosion and suspension of river channel material occurs immediately upon exposure to rapidly moving flow. All sediment in the river channel erodes upon the first exposure to flowing water. Subsequent raising and lowering of reservoir levels does not erode more sediment beyond the initially defined active channel.
- Trapping efficiency was based on weighted average particle sizes and flows discussed more thoroughly below.
- Suspended sediment from Copco 1 is resettled in Iron Gate, based on standard settling analysis techniques[1]. The settled sediment is distributed evenly over the wetted area of Iron Gate Reservoir at the time of settling.
- Sediment eroded from upper reaches of Iron Gate Reservoir is resettled in the remaining reservoir and distributed evenly over the reservoir wetted area present when the erosion occurs.
- No settling, redistribution, and re-erosion of sediment from upper to lower reaches *within* Copco 1 was included in the analysis.
- As material settles in Iron Gate Reservoir and is distributed evenly over the area of the reservoir present at the time that settling occurs, some of that material will settle in the inundated river channel in Iron Gate Reservoir. That portion of sediment eroded and resettled, from Copco 1 and upper reaches of Iron Gate reservoirs that settles in the area of the *river channel* only, is eroded again as the water surface elevation decrease in Iron Gate.

Pierre Y. Julien, *River Mechanics* (Cambridge University Press, 2002), 4.3.2 Riverbed aggredation and degradation, p. 115

Analysis Techniques and Approach

Sediment Characteristics

The volume of sediment trapped in the reservoirs is presented in the November 2006 report to FERC. Once mobilized, sediment smaller than very fine sand can be assumed to travel as suspended sediment. Eighty four percent of all material trapped in the reservoirs is smaller than very fine sand (0.125 mm). Since a large fraction of all material trapped in the reservoirs is fine sediment, ***all eroded material was assumed to be eroded as suspended sediment***. (Approximately 84% of the sediment is finer than 0.125 mm)

Trapping and Re-eroding Sediment

Trapping efficiency was calculated as a function of reservoir elevation as shown in Table 2 using the trapping efficiency equation $T_{Ei} = \frac{C_{0i} - C_i}{C_{0i}} = 1 - e^{-X\omega_i/hv}$ [2]. Trapping efficiency analysis for Iron Gate Reservoir assumed the average particle size entering the reservoir was 0.006 mm and an average reservoir flow of 3,000 cfs.

For Iron Gate Reservoir, sediment eroded from Copco 1 and upstream in Iron Gate was divided between sediment that eroded, stayed in suspension, and immediately passed through the reservoir and sediment re-trapped as shown Table 2. It was assumed that re-trapped sediment was uniformly distributed over the remaining reservoir area. As reservoir elevation dropped, trapped sediment deposited *in the river channel area* was re-eroded based on the ratio of reservoir area to river channel area remaining at a particular reservoir elevation.

For instance, as shown in Table 2, when Iron Gate reservoir water surface elevation is lowered to 2290, 53% of sediment eroded in Iron Gate Reservoir at that elevation and coming into to the reservoir from Copco 1 is trapped and distributed evenly over the remaining reservoir area.

Longitudinal Extents

The model simulates the flow through Copco 1 and Iron Gate dams. Copco 2 Dam, which is located between Copco 1 and Iron Gate dams, is too small to contribute to erosion or trapping of sediment. J. C. Boyle dam located upstream contains approximately 650,000 cubic yards of sediment, most of which is sand. J. C. Boyle reservoir is relatively small and shallow compared to Copco 1 and Iron Gate reservoirs. For this analysis it was assumed that J. C. Boyle reservoir was lowered quickly at the start of the reservoir lowering process. Most of the sediment from that lowering process

[2] Ibid.

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will be trapped in Copco 1. For this analysis J. C. Boyle sediment was distributed evenly over Copco 1 reservoir area.

TSS Calculation

TSS is calculated as discussed above and provided in ppm (part per million by weight, or mg/litter). Again, as a preliminary assessment, all the sediment in transport is assumed to be in suspension and counted for in the TSS.

Sediment Volume Eroded

Reservoir sediment volume calculation is thoroughly discussed in the December 2006 FERC Report. The volume of sediment eroded per day for Iron Gate Reservoir is linearly interpolated from Table 4, the volume of sediment in the eroded river channel by reservoir surface elevation. The volume eroded per daily increment is interpolated from the values presented based on the difference in volume of sediment corresponding to the water surface elevations on succeeding days. For instance, if Iron Gate reservoir dropped 5 feet in one day from 2215 to 2210 the average volume of sediment contained in the river channel for that increment would be (697,171 +711,343)/2 = 704,257 cubic feet per foot of drop. For the total drop of 5 feet the volume of sediment eroded would be 704,257 x 5 feet = 35.2 million cubic feet or 130,000 cubic yards. The average sediment weight used throughout was 43 pounds per cubic foot based on discussions presented in the December FERC report. That volume would be suspended and eroded from the reservoir or re-trapped as discussed elsewhere.

Water Volume Released

The water surface elevation for both reservoirs is set at the full reservoir elevation at the time of initiating the reservoir drawdown. The out flowing water volume for each daily increment is governed by the difference in flow into and out of the reservoir. This flow difference will determine the total water volume in the reservoir at the end of each day and the change in water surface elevation. Table 3 shows the relationship between total water volume in the reservoir and surface elevation. That relationship was developed from bathymetric survey information provided by PacifiCorp.

Water surface elevation changes were calculated by multiplying the difference between the rates of flow into and out of the reservoir by the amount of time that the flow occurred. In this case the time span used was one day because all flow records are provided in cubic feet per second for average *daily* flow. The maximum reservoir elevation change is limited to the prescribed lowering rate or the amounted limited by the outlet facilities to pass incoming flow. When inflow to the reservoir exceeds the outlet capacity the spreadsheet adds water volume and calculates a new elevation based on the relationship between water volume and elevation shown in Table 3.

The maximum rate of reservoir lowering used in analysis in the FERC report was 3 feet per day. Higher rates of lowering the reservoir were investigated to determine the possibility of lowering the reservoir completely before high flows re-elevated the water surface.

Table 1 Sediment Volume Calculation for Iron Gate Reservoir.

Reservoir Elevation ft	Original Area ft2	Current Area ft2	Sediment Volume ft3
2325	41,837,908	40,876,586	
2320	38,699,444	38,376,271	3,211,237
2315	36,400,983	35,875,957	2,120,496
2310	34,102,522	33,375,643	3,129,761
2305	32,125,703	30,883,910	4,921,680
2300	30,148,885	28,443,723	7,367,387
2295	28,289,221	26,109,270	9,712,782
2290	26,429,558	24,275,980	10,833,822
2285	24,679,807	22,464,754	10,921,574
2280	22,930,056	20,738,715	11,015,983
2275	21,191,581	19,015,755	10,917,915
2270	19,453,105	17,302,701	10,815,575
2265	18,017,509	15,735,474	11,081,098
2260	16,581,912	14,565,138	10,747,021
2255	15,300,829	13,395,827	9,804,441
2250	14,019,746	12,228,903	9,239,613
2245	13,166,842	11,107,139	9,626,364
2240	12,313,938	10,076,363	10,743,194
2235	11,257,462	9,070,041	11,062,490
2230	10,200,986	8,111,975	10,691,079
2225	9,292,703	7,179,554	10,505,399
2220	8,384,420	6,286,461	10,527,768
2215	7,402,879	5,365,129	10,339,270
2210	6,421,338	4,405,774	10,133,284
2205	4,856,050	3,469,462	8,505,379
2200	3,290,762	2,560,457	5,292,233
2195	2,468,072	1,761,612	3,591,914
2190	1,645,381	1,077,792	3,185,122
2185	1,234,036	568,154	3,083,676
2180	822,691	218,863	3,174,273
2175	617,018	62,400	2,896,115
2170			
	Volume Cubic Feet		239,197,945
	Volume Cubic Yards		8,859,183

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Table 2 Iron Gate Trapping vs. Elevation

Reservoir Elevation	River Area	Reservoir Area	River Area as % of Reservoir Area	% of Incoming Sediment Trapped
2,173	411,345	411,345	100%	0%
2,177	617,018	617,018	100%	1%
2,180	658,152	822,691	80%	1%
2,185	1,079,076	1,234,036	87%	2%
2,190	1,500,000	1,645,381	91%	3%
2,195	1,850,000	2,468,072	75%	5%
2,200	2,200,000	3,290,762	67%	8%
2,205	2,887,500	4,856,050	59%	10%
2,210	3,575,000	6,421,338	56%	13%
2,215	3,875,000	7,402,879	52%	15%
2,220	4,175,000	8,384,420	50%	18%
2,225	4,325,000	9,292,703	47%	20%
2,230	4,475,000	10,200,986	44%	22%
2,235	4,612,500	11,257,462	41%	25%
2,240	4,750,000	12,313,938	39%	27%
2,245	4,937,500	13,166,842	37%	29%
2,250	5,125,000	14,019,746	37%	32%
2,255	5,475,000	15,300,829	36%	34%
2,260	5,825,000	16,581,912	35%	37%
2,265	5,975,000	18,017,509	33%	39%
2,270	6,125,000	19,453,105	31%	42%
2,275	6,462,500	21,191,581	30%	45%
2,280	6,800,000	22,930,056	30%	48%
2,285	7,087,500	24,679,807	29%	51%
2,290	7,375,000	26,429,558	28%	53%
2,295	7,562,500	28,289,221	27%	56%
2,300	7,750,000	30,148,885	26%	59%
2,305	7,962,500	32,125,703	25%	62%
2,310	8,175,000	34,102,522	24%	65%
2,320	8,625,000	38,699,444	22%	69%
2,328	8,900,000	41,837,908	21%	72%

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Table 3 Iron Gate Reservoir Water Volume vs. Elevation

Total Remaining Reservoir Water Volume CF	Reservoir Elevation - feet
-	2170
1,500,000	2175
3,599,271	2180
8,741,087	2185
15,939,629	2190
26,223,261	2195
40,620,346	2200
60,987,376	2205
89,180,845	2210
123,741,385	2215
163,209,631	2220
207,402,437	2225
256,136,658	2230
309,782,777	2235
368,711,276	2240
432,413,226	2245
500,379,695	2250
573,681,131	2255
653,387,984	2260
739,886,537	2265
833,563,072	2270
935,174,787	2275
1,045,478,878	2280
1,164,503,533	2285
1,292,276,943	2290
1,429,073,890	2295
1,575,169,154	2300
1,730,855,623	2305
1,896,426,184	2310
2,072,684,945	2315
2,260,436,013	2320
2,461,779,392	2325

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Table 4 Iron Gate River Channel Sediment Volume versus Elevation

Water Surface Elevation feet	Rate of Sediment Volume ft3/ft	Eroded Volume in Increment - ft3
2181	500	
2190	219,137	1,095,684
2195	247,124	1,235,621
2200	364,106	1,820,532
2205	585,171	2,925,856
2210	697,171	3,485,856
2215	711,343	3,556,716
2220	724,312	3,621,559
2225	722,773	3,613,864
2230	735,548	3,677,738
2235	761,101	3,805,504
2240	739,133	3,695,666
2245	662,295	3,311,476
2250	635,687	3,178,433
2255	674,547	3,372,734
2260	739,396	3,696,982
2265	762,381	3,811,905
2270	744,113	3,720,565
2275	751,154	3,755,770
2280	757,901	3,789,506
2285	751,406	3,757,029
2290	745,368	3,726,842
2295	668,241	3,341,204
2300	506,877	2,534,386
2305	338,612	1,693,061
2310	215,328	1,076,640
2315	145,890	729,452
2320	220,934	1,104,668
2325	0	

Total Eroded 2,930,935 CY

Table 5 Copco 1 Sediment Volume Calculation

Reservoir Elevation ft	Original Area ft2	Current Area ft2	Sediment Volume ft3
2613	43,055,644	43,055,644	-
2602	40,446,283	40,446,283	-
2595	38,274,009	35,847,555	8,492,586
2590	35,642,177	32,562,750	13,764,699
2585	33,435,915	29,277,945	18,093,491
2580	30,645,077	26,214,667	21,470,949
2575	27,140,159	23,431,056	20,348,783
2570	24,041,990	20,790,592	17,401,252
2565	21,988,969	18,308,980	17,328,465
2560	19,659,281	16,182,001	17,893,169
2555	17,638,060	14,401,244	16,785,236
2550	15,234,457	12,226,029	15,613,108
2545	14,088,407	9,712,079	18,461,889
2540	10,411,023	7,451,646	18,339,261
2535	8,740,306	5,384,031	15,789,131
2530	7,164,260	3,918,404	16,505,327
2525	4,880,439	2,854,105	13,180,475
2520	3,850,695	1,698,216	10,447,033
2515	3,199,337	488,998	12,157,044
2510	1,035,338	65,792	9,199,713
2505	72,646	41,399	2,501,982
2500	49,083	0	200,826
2495	28,105	0	192,970
2490	9,102	0	93,016
	Volume Cubic Feet		284,260,407
	Volume Cubic Yards		10,528,163

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Table 6 Copco 1Water Volume versus Elevation

Water Volume ft3	Reservoir Elevation ft
(0)	2,489
93,016	2,490
285,986	2,495
590,309	2,500
3,360,268	2,505
13,946,958	2,510
31,572,038	2,515
53,399,873	2,520
83,511,619	2,525
123,273,034	2,530
171,151,357	2,535
232,399,930	2,540
305,707,090	2,545
387,888,382	2,550
481,131,733	2,555
585,252,357	2,560
700,329,754	2,565
828,285,126	2,570
972,748,217	2,575
1,132,950,696	2,580
1,305,645,924	2,585
1,490,436,387	2,590
1,771,423,013	2,595
2,239,272,422	2,602

Table 7 Copco Eroded Sediment Volume versus Elevation

Elevation	Volume Cf/ft	Volume in Increment cf
2,485	4,100	93,016
2,495	8,507	192,970
2,500	8,853	200,826
2,505	110,296	2,501,982
2,510	405,556	9,199,713
2,515	535,925	12,157,044
2,520	460,542	10,447,033
2,525	581,042	13,180,475
2,530	727,613	16,505,327
2,535	696,040	15,789,131
2,540	808,459	18,339,261
2,545	813,865	18,461,889
2,550	688,281	15,613,108
2,555	739,952	16,785,236
2,560	788,794	17,893,169
2,565	763,900	17,328,465
2,570	767,108	17,401,252
2,575	897,046	20,348,783
2,580	946,515	21,470,949
2,585	797,625	18,093,491
2,590	606,796	13,764,699
2,595	267,416	8,492,586

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